Prompt gamma rays from the spontaneous fission of $^{252}\text{Cf}$ and their angular distributions

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Outline

• Introduction
• Experimental setup
• Data treatment
• Preliminary results
• Discussion
• Summary & outlook
Introduction

• For many years: precise measurement of prompt fission γ-ray spectra (PFGS)
Introduction

For many years: precise measurement of prompt fission $\gamma$-ray spectra (PFGS)

Determination of characteristics:

- $< M_\gamma >$, $< \varepsilon_\gamma >$, and $< E_{\gamma,\text{tot}} >$
Introduction

• For many years: precise measurement of prompt fission $\gamma$-ray spectra (PFGS)

• Determination of characteristics:
  • $< M_\gamma >$, $< \varepsilon_\gamma >$, and $< E_{\gamma,\text{tot}} >$

• Studies of the dependence of $A$, $Z$, and $E_x$
# Introduction

PFGS characteristics as function of $A$, $Z$ and $E_x$

## Compound Systems
Introduction

PFGS characteristics as function of $A$, $Z$ and $E_x$

Andreas Oberstedt

FIESTA 2017, Santa Fe (New Mexico), September 18-22, 2017
Introduction
The Co-workers
Introduction
The Co-workers

Quote: “It started as a family business... now it's a "gang" ;-)”

Patrick Talou, July 6, 2017
Introduction
“The Gang”


PhD students
Introduction

• For many years: precise measurement of prompt fission \( \gamma \)-ray spectra (PFGS)

• Determination of characteristics:
  • \( \langle M_\gamma \rangle \), \( \langle \varepsilon_\gamma \rangle \), and \( \langle E_{\gamma,\text{tot}} \rangle \)

• Studies of the dependence of \( A \), \( Z \), and \( E_x \)

• Now: focus on the de-excitation process of fission fragments
Introduction
Sequential emission of neutrons and $\gamma$-rays

According to: Litaize & Serot, PRC 82, 054616 (2010)
Introduction
Sequential emission of neutrons and $\gamma$-rays

According to: Litaize & Serot, PRC 82, 054616 (2010)
Introduction

• For many years: precise measurement of prompt fission $\gamma$-ray spectra (PFGS)
• Determination of characteristics:
  • $< M_\gamma >$, $< \varepsilon_\gamma >$, and $< E_{\gamma,\text{tot}} >$
• Studies of dependence of $A$, $Z$, and $E_x$
• Now: focus on the de-excitation process of fission fragments
• Measurement of PFG angular distributions!
Experimental setup

Frisch grid ionization chamber + LaBr$_3$ detector

Correlations between fission fragments and $\gamma$-rays
Data treatment

Detector response matrix vs. transformation matrix

\[
\begin{pmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_n
\end{pmatrix}
= 
\begin{pmatrix}
  r_{11} & r_{12} & \cdots & r_{1n} \\
  r_{21} \\
  \vdots \\
  r_{n1} & \cdots & r_{nn}
\end{pmatrix}
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]
Data treatment

Detector response matrix vs. transformation matrix

\[
\begin{pmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_n
\end{pmatrix} =
\begin{pmatrix}
  r_{11} & r_{12} & \cdots & r_{1n} \\
  r_{21} & \ddots & \ddots & \vdots \\
  \vdots & \ddots & \ddots & \vdots \\
  r_{n1} & \cdots & r_{nn}
\end{pmatrix}
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]

usually simulated (GEANT4, PENEOPE)
Data treatment

Detector response matrix vs. transformation matrix

\[
\begin{align*}
\text{measured spectrum} & \quad \text{response matrix} & \quad \text{emission spectrum} \\
\begin{pmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{pmatrix}
& \begin{pmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} \\
\vdots \\
r_{n1} & \cdots & r_{nn}
\end{pmatrix}
& \begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
\end{align*}
\]

diagonalized

\[
\begin{pmatrix}
r'_{11} & 0 & \cdots & 0 \\
0 & r'_{22} \\
\vdots & \vdots & \ddots & \vdots \\
0 & \cdots & 0 & r'_{nn}
\end{pmatrix}
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
\]
Data treatment
Detector response matrix vs. transformation matrix

\[
\begin{pmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_n
\end{pmatrix}
= 
\begin{pmatrix}
  r_{11} & r_{12} & \cdots & r_{1n} \\
  r_{21} & r_{22} & \cdots & r_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  r_{n1} & r_{n2} & \cdots & r_{nn}
\end{pmatrix}
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]

if both are known …

\[
\begin{pmatrix}
  r_{11}' & 0 & \cdots & 0 \\
  0 & r_{22}' & \cdots & 0 \\
  \vdots & \vdots & \ddots & \vdots \\
  0 & \cdots & 0 & r_{nn}'
\end{pmatrix}
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]
Data treatment

Detector response matrix vs. transformation matrix

measured spectrum

\[
\begin{pmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{pmatrix}
\]

response matrix

\[
\begin{pmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
r_{n1} & \cdots & r_{nn}
\end{pmatrix}
\]

emission spectrum

\[
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
\]

\[
\begin{pmatrix}
y_1 \\
y_2 \\
\vdots \\
y_n
\end{pmatrix} = \begin{pmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & \ddots & \cdots & \vdots \\
\vdots & \ddots & \ddots & \vdots \\
r_{n1} & \cdots & r_{nn}
\end{pmatrix} \begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_n
\end{pmatrix}
\]

... this matrix can be determined, e.g. by

\[
r'_{ii} = \frac{y_i}{x_i}
\]
### Data treatment

**Detector response matrix vs. transformation matrix**

<table>
<thead>
<tr>
<th>Measured spectrum</th>
<th>Response matrix</th>
<th>Emission spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_1 )</td>
<td>( r_{11} ) ( r_{12} ) … ( r_{1n} )</td>
<td>( x_1 )</td>
</tr>
<tr>
<td>( y_2 )</td>
<td>( r_{21} )</td>
<td>( x_2 )</td>
</tr>
<tr>
<td>…</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>( y_n )</td>
<td>( r_{n1} ) ( r_{n2} ) … ( r_{nn} )</td>
<td>( x_n )</td>
</tr>
</tbody>
</table>

\[
\begin{pmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_n
\end{pmatrix}
= 
\begin{pmatrix}
  r_{11} & r_{12} & \cdots & r_{1n} \\
  r_{21} & \ddots & \vdots & \vdots \\
  \vdots & \ddots & \ddots & \vdots \\
  r_{n1} & \cdots & r_{nn}
\end{pmatrix}
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]

\[
\begin{pmatrix}
  r'_{11} & 0 & \cdots & 0 \\
  0 & r'_{22} & \ddots & \vdots \\
  \vdots & \ddots & \ddots & 0 \\
  0 & \cdots & 0 & r'_{nn}
\end{pmatrix}
= 
\begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix}
\]

… this matrix can be determined, e.g. by \( r'_{ii} = y_i / x_i \)!

Applied to other measurements (same conditions)!
Preliminary results
Prompt fission $\gamma$-ray spectra (PFGS)

$^{252}\text{Cf}(sf)$

Photons / (MeV fission)

$E_\gamma$ (MeV)

Good agreement between this work and a previously measured spectrum
Preliminary results
Prompt fission γ-ray spectra (PFGS)

Good agreement between this work and a previously measured spectrum \( \rightarrow \) repeat for different \( \cos \theta \) bins!
Preliminary results
Angular distribution

Fit: \( W(\theta) = A_0 \left[ 1 + \left\{ \frac{A_2}{A_0} \right\} P_2(\cos\theta) + \left\{ \frac{A_4}{A_0} \right\} P_4(\cos\theta) \right] \)

Statistical uncertainties only!
Preliminary results
Angular distribution

Fit result: \( \{A_2/A_0\} = 0.13 \pm 0.03 \)
Preliminary results
Angular distribution

**Angular Distributions in $^{109}$Te**

- Typically $A_4/A_0$ is close to zero
- And $A_2/A_0 \sim +0.3$ for a pure quadrupole ($\Delta I = 2$) transition
- Or $A_2/A_0 \sim -0.3$ for a pure dipole ($\Delta I = 1$) transition
Preliminary results
Angular distribution

Theory: \[ \{A_2/A_0\} = + 0.3 \text{ for quadrupole radiation} \]
\[ \{A_2/A_0\} = -0.3 \text{ for dipole radiation} \]

Statistical + systematic uncertainties!
Preliminary results
Angular distributions for 500 keV energy bins

$\rightarrow$ again: fit of Legendre polynomials

$\rightarrow$ decomposition of multipolarities $L = 1$ and $2$
Preliminary results
Multipolarity-dependent PFGS

\[ 252\text{Cf}(sf) \]

\[ \text{Photons } / \, (\text{MeV fission}) \]

\[ \text{E}_\gamma \, (\text{MeV}) \]

→ multipolarity-dependent spectra
→ multipolarity-dependent PFGS characteristics
Discussion

Previously measured angular distributions *)

\[ W(\theta) = \frac{I(\theta)}{A_0} \]

*) Hoffman, Phys. Rev. 133 (1964)
Discussion
Previously measured angular distributions *)

Good agreement in dominating E2 character!

*) Hoffman, Phys. Rev. 133 (1964)
Discussion
Comparison with FIFRELIN calculations *

Good agreement between integral spectra!

*) A. Chebboubi, priv. comm.
Discussion
Comparison with FIFRELIN calculations *

Good agreement between integral spectra!
But FIFRELIN also provides multipolarity-dependent PFGS.

*) A. Chebboubi, priv. comm.
## Discussion

### Comparison with FIFRELIN calculations *)

<table>
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<tr>
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<th>Calculations (FIFRELIN)</th>
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<tr>
<td>$\overline{M}_\gamma$</td>
<td>8.28 ± 0.51</td>
<td>8.28 (adjusted)</td>
</tr>
<tr>
<td>$\overline{M}_\gamma$ (L = 1)</td>
<td>2.31 (28 %)</td>
<td>3.20 (39 %)</td>
</tr>
<tr>
<td>$\overline{M}_\gamma$ (L = 2)</td>
<td>5.97 (72 %)</td>
<td>1.45 (17 %)</td>
</tr>
<tr>
<td>$\overline{M}_\gamma$ (unknown)</td>
<td>---</td>
<td>3.63 (44 %)</td>
</tr>
<tr>
<td>$\overline{E}_\gamma$</td>
<td>6.51 ± 0.76 (MeV)</td>
<td>6.30 (MeV)</td>
</tr>
<tr>
<td>$\overline{E}_\gamma$ (L = 1)</td>
<td>1.99 (MeV)</td>
<td>3.00 (MeV)</td>
</tr>
<tr>
<td>$\overline{E}_\gamma$ (L = 2)</td>
<td>4.52 (MeV)</td>
<td>1.49 (MeV)</td>
</tr>
<tr>
<td>$\overline{E}_\gamma$ (unknown)</td>
<td>---</td>
<td>1.81 (MeV)</td>
</tr>
</tbody>
</table>

*) A. Chebboubi, priv. comm.
Discussion
Comparison with FIFRELIN calculations *)

From our observations: unknown transitions $\rightarrow L = 2$, $L = 2 + \text{unknown} \rightarrow L = 2'$.

*) A. Chebboubi, priv. comm.
**Discussion**

**Comparison with FIFRELIN calculations *)**

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<td>5.97 (72 %)</td>
<td>5.08 (61 %)</td>
</tr>
<tr>
<td>$\bar{M}_\gamma$ (unknown)</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>$\bar{E}_\gamma$</td>
<td>$0.79 \pm 0.10$ (MeV)</td>
<td>0.76 (MeV)</td>
</tr>
<tr>
<td>$\bar{E}_\gamma$ (L = 1)</td>
<td>0.86 (MeV)</td>
<td>0.94 (MeV)</td>
</tr>
<tr>
<td>$\bar{E}_\gamma$ (L = 2')</td>
<td>0.76 (MeV)</td>
<td>0.65 (MeV)</td>
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*) A. Chebboubi, priv. comm.
Summary

- Measured angular distribution of prompt $\gamma$ rays from $^{252}$Cf(sf) → dominant E2 character, in good agreement with previous measurements.
- With $\langle M_\gamma \rangle \approx 8.3$ follows:
  - $\langle M_{\gamma,L=1} \rangle \approx 2.3$ and $\langle M_{\gamma,L=2} \rangle \approx 6.0$
Summary

Sequential emission of neutrons and \(\gamma\)-rays

\[ \Delta E_n \approx 8 \text{ MeV} \]
Summary

\[ \Delta E_n \approx 8 \text{ MeV} \]

\[ \Delta E_\gamma \approx 6.5 \text{ MeV} \]

Entry region for primary fragments

Entry region for secondary fragments

\{ \text{statistical } \gamma\text{-rays (dipole transitions)} \}

\{ \text{discrete levels (quadrupole transitions)} \}
Summary

ΔE_n ≈ 8 MeV

ΔE_γ ≈ 2.0 MeV

ΔE_γ ≈ 4.5 MeV

preliminary!

statistical γ-rays (dipole transitions)

discrete levels (quadrupole transitions)
Summary

Entry region for primary fragments

Entry region for secondary fragments

\[ \Delta E_n \approx 8 \text{ MeV} \]

\[ \Delta E_\gamma \approx 2.0 \text{ MeV} \]

\[ \Delta E_\gamma \approx 4.5 \text{ MeV} \]

\[ S_n/2 \]

\( \gamma \)

\( \gamma \)

\( \gamma \)

\( \gamma \)

\( \gamma \)

statistical \( \gamma \)-rays (dipole transitions)

\{ discrete levels (quadrupole transitions) \}

preliminary!
Summary

• Measured angular distribution of prompt $\gamma$ rays from $^{252}$Cf(sf) $\rightarrow$ dominant E2 character, in good agreement with previous measurements

• With $\langle M_\gamma \rangle \approx 8.3$ follows
  • $\langle M_{\gamma,L=1} \rangle \approx 2.3$ and $\langle M_{\gamma,L=2} \rangle \approx 6.0$

• Average spin of fission fragments is $J \approx 12 \hbar$, which seems a bit high, but still reasonable
Summary

\[ \Delta E_n \approx 8 \text{ MeV} \]
\[ \Delta E_\gamma \approx 2.0 \text{ MeV} \]
\[ \Delta E_\gamma \approx 4.5 \text{ MeV} \]

Entry region for primary fragments
Entry region for secondary fragments

\[ \Delta J \approx 12 \hbar \]

\[ \text{S}_n/2 \]

statistical \( \gamma \)-rays (dipole transitions)

discrete levels (quadrupole transitions)

preliminary!
Summary

• Measured angular distribution of prompt $\gamma$ rays from $^{252}$Cf(sf) $\rightarrow$ dominant E2 character, in good agreement with previous measurements.

• With $\langle M_\gamma \rangle \approx 8.3$ follows:
  • $\langle M_{\gamma,L=1} \rangle \approx 2.3$ and $\langle M_{\gamma,L=2} \rangle \approx 6.0$

• Average spin of fission fragments is $J \approx 12 \hbar$, which seems a bit high, but still reasonable.

• Comparison with FIFRELIN calculations shows rather good agreement ...
... that is even better with a more realistic (?) assumption \( \{A_2/A_0\} \approx -0.2 \) for dipole radiation,

leading to

- \( \langle M_{\gamma,L=1} \rangle \approx 2.8 \) (34 %) and
- \( \langle M_{\gamma,L=2} \rangle \approx 5.5 \) (66 %)

These results have to be compared with other related information on fission fragments, such as

- average neutron separation energies
- average moments of inertia etc.
The collaborators

A. Oberstedt, R. Billnert, A. Gatera, A. Göök, S. Oberstedt

Thank you!